The Carbon Balance Observatory (CARBO) Instrument for Space-based Observation of Greenhouse Gases

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The CARBO Team

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Overview of Presentation

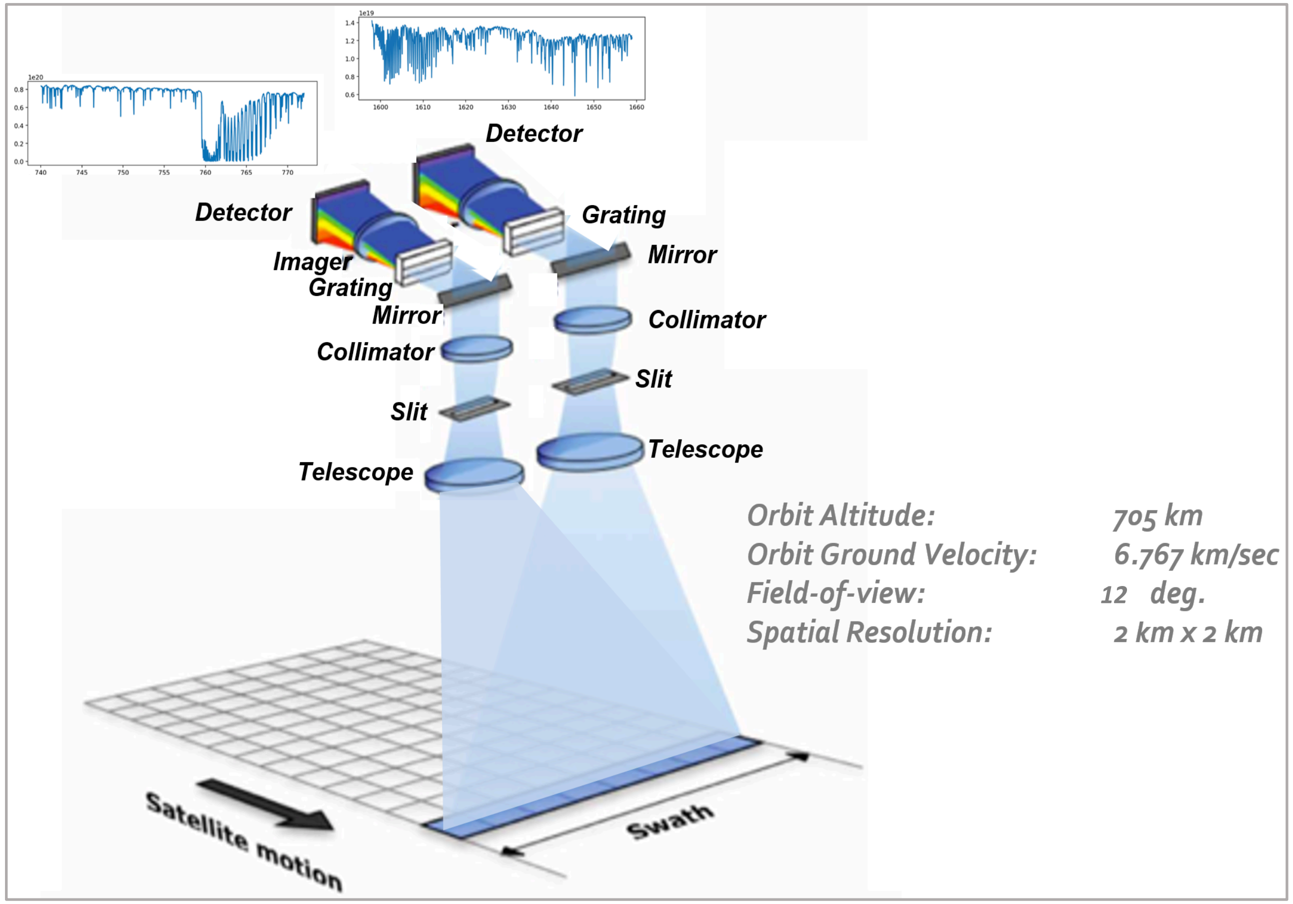
- Programmatic overview
- CARBO instrument concept
- Instrument architecture
- Key technologies
  - Immersion gratings
  - Polarization sensing
  - Large format CHROMA-D/GeoSnap focal plane arrays
- Instrument radiometric performance estimate
- Summary and conclusion

Programmatic Overview

- Funded by Instrument Incubator Program (IIP)
  - NASA’s Earth Science Technology Office (ESTO)
- Institutions:
  - Jet Propulsion Laboratory
  - University of Texas at Austin
  - Caltech
- Goal:
  - Develop a new, more capable suite of instruments to measure the green house gasses for better understanding of carbon climate.
  - Advance new technology immersion gratings and modular instrument architecture.

CARBO Instrument Concept

- Wide-swath imaging spectrometer
  - FOV: 12 degree
  - Ground swath: 148 km
- Spatial resolution element 2 km x 2 km
- Contiguous spatial sampling
- Weekly revisit rate
- Low Earth orbit (LEO)
- Adds CH4 and CO to the CO2 and Solar Induced Fluorescence (SIF) measurements pioneered by the Orbiting Carbon Observatory (OCO-2/3)
  - increases ability to disentangle carbon fluxes into their constituent components
- Modular architecture
- New technology
  - Immersion grating
  - CHROMA-D/GeoSnap focal plane array: a large-format, low-noise detector optimized for imaging spectroscopy
  - Polarization sensing



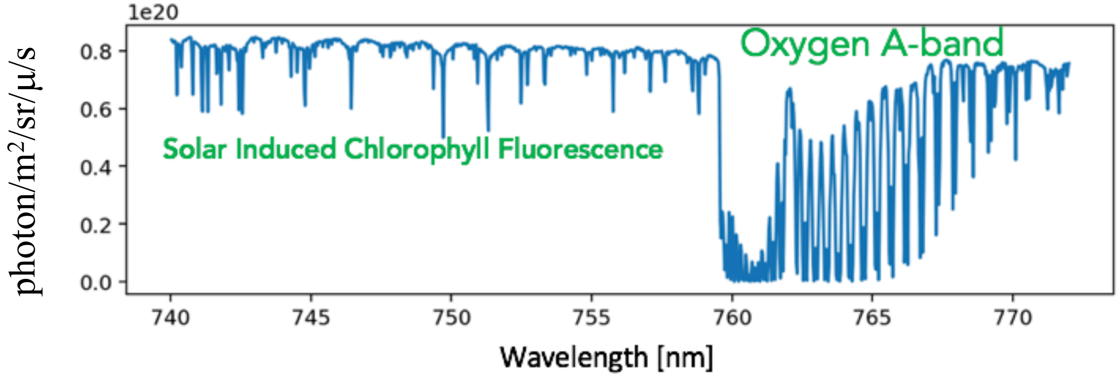
CARBO Science Requirements

CARBO Requirements	Design, Build, Field Test		Design	
	Instrument 1	Instrument 2	Instrument 3	Instrument 4
Spectral Range (nm)	745 -772 ($\Delta\lambda$ = 27 nm)	1598 – 1659 ($\Delta\lambda$ = 61 nm)	2045 – 2080 ($\Delta\lambda$ = 35 nm)	2305 – 2350 ($\Delta\lambda$ = 45 nm)
Measurement Targets	O_2, SIF	CO_2, CH_4	CO_2	CO_2, CH_4, H_2O
SNR @ 5% albedo and 65^O SZA	> 300	> 350	> 150	>100
Spectral resolution FWHM (nm) at λ_{ave}	0.05	0.15	0.10	0.12
Spectral Resolving power at λ_{max}	15,440	11,060	20,800	19,583
Required Precision	X_{CO2}<1.5 ppm, X_{CH4}<7 ppb, X_{CO}<5 ppb, SIF <20%			

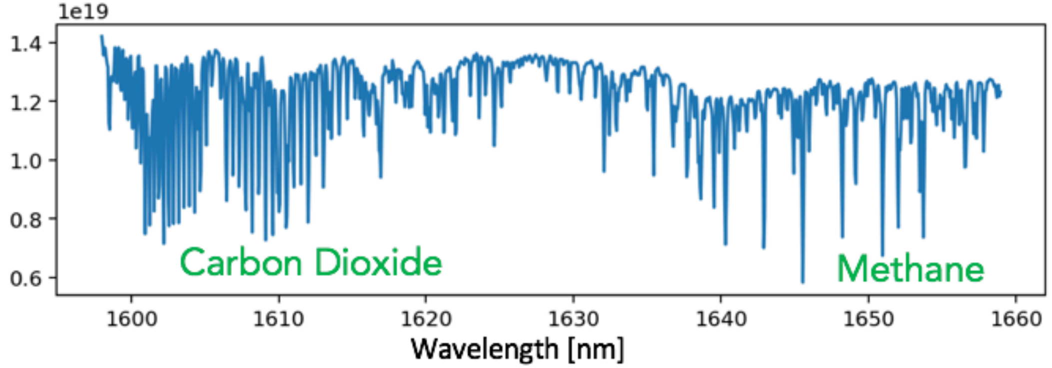
- Nominal bright case – SNR @ SZA = 35 deg and albedo = 30%
- The SNR case for SZA = 65 deg and 5% albedo is the driving/limiting dark case

CARBO Instrument Science Bands

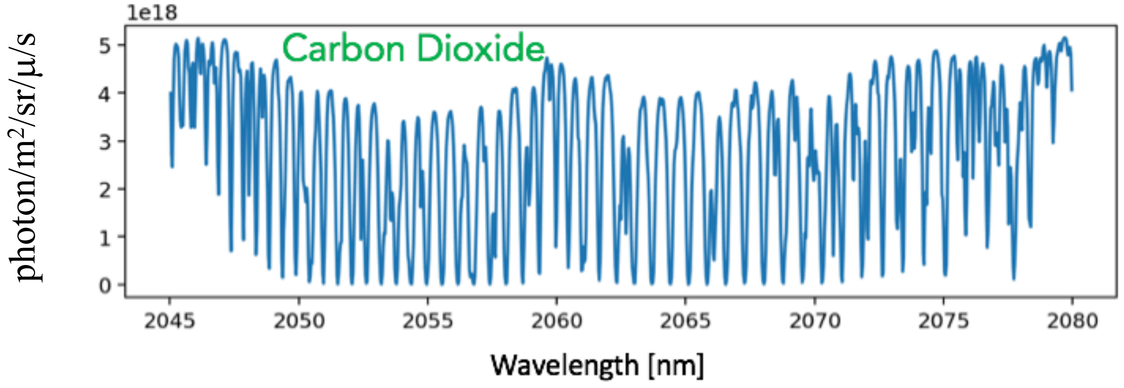
Instrument 1



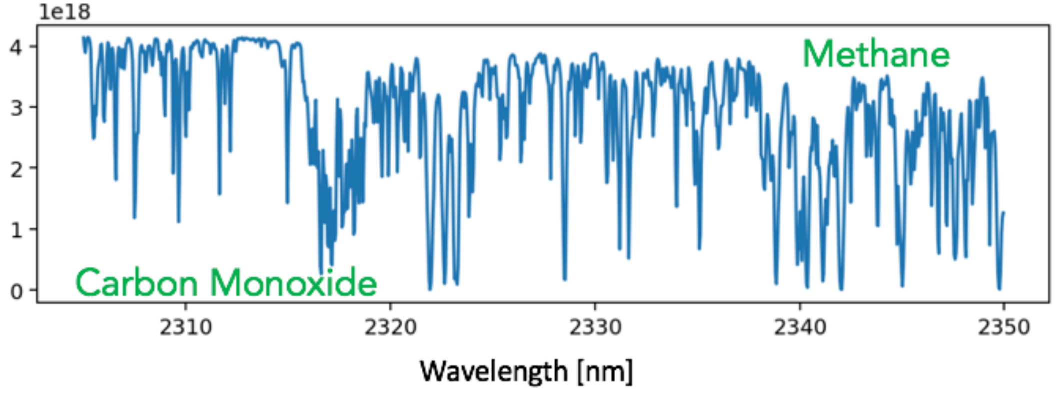
Instrument 2



Instrument 3



Instrument 4

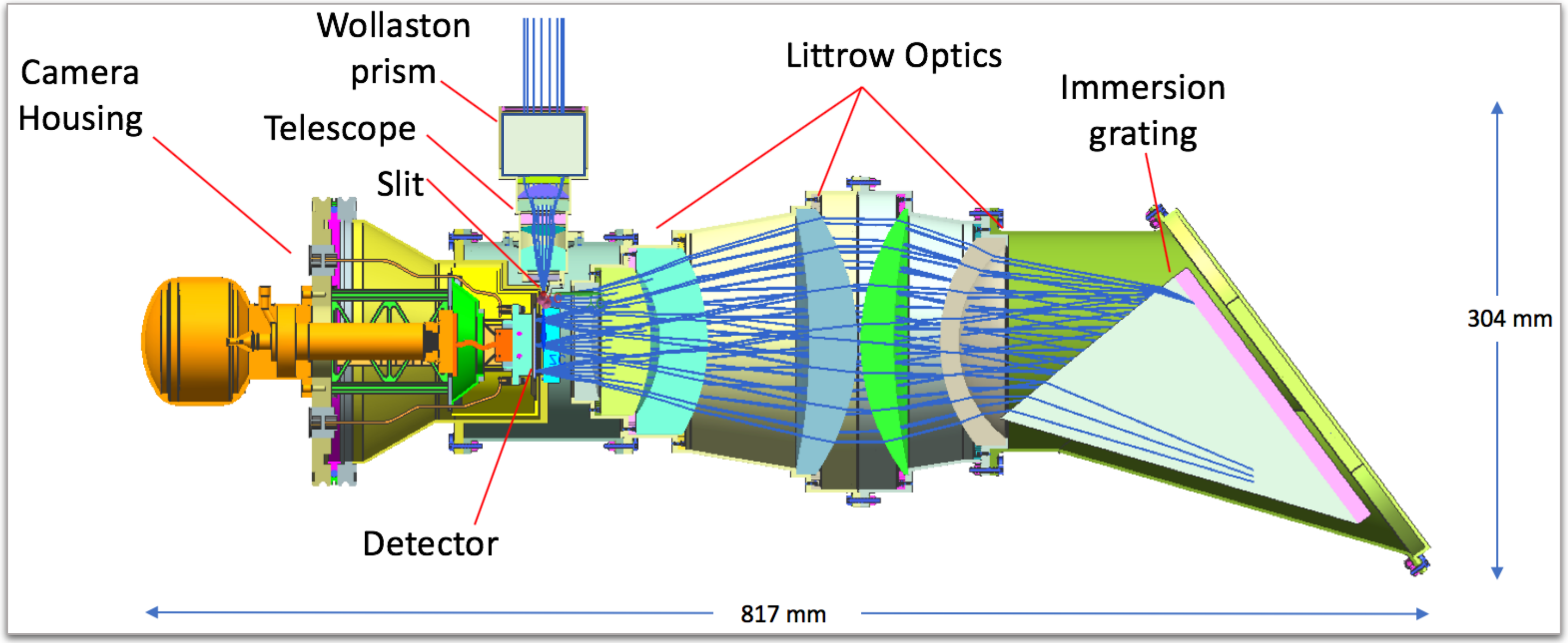


Conceptual **Opto-Mechanical** Layout

Instrument 1

(*745 – 772 nm, for Oxygen-A band and SIF Remote Sensing*)

- Telescope aperture diameter: 25 mm
- Telescope focal length: 52.8 mm
- Telescope F/# : 2.11
- Ground Sample Distance: 400 m
- Slit width: 60 um
- Wavelength range : 27 nm
- Spectral Resolution: 0.05 nm
- R = 15,400
- Spectral dispersion: 1080 pixels



Dimension are for a design with CHROMA-A (30 μ pixel). The design for CHROMA-D/GeoSnap scales down in size for 18 μ pixels.

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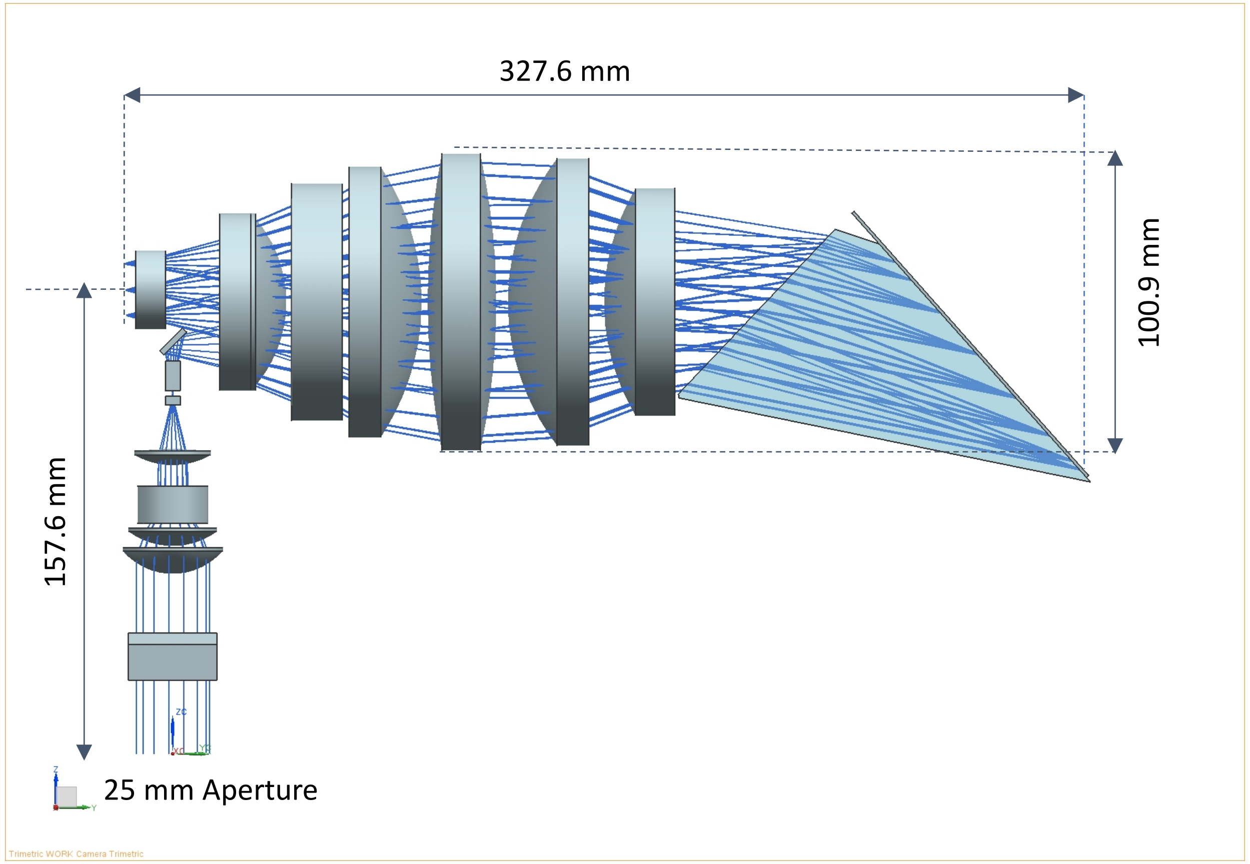
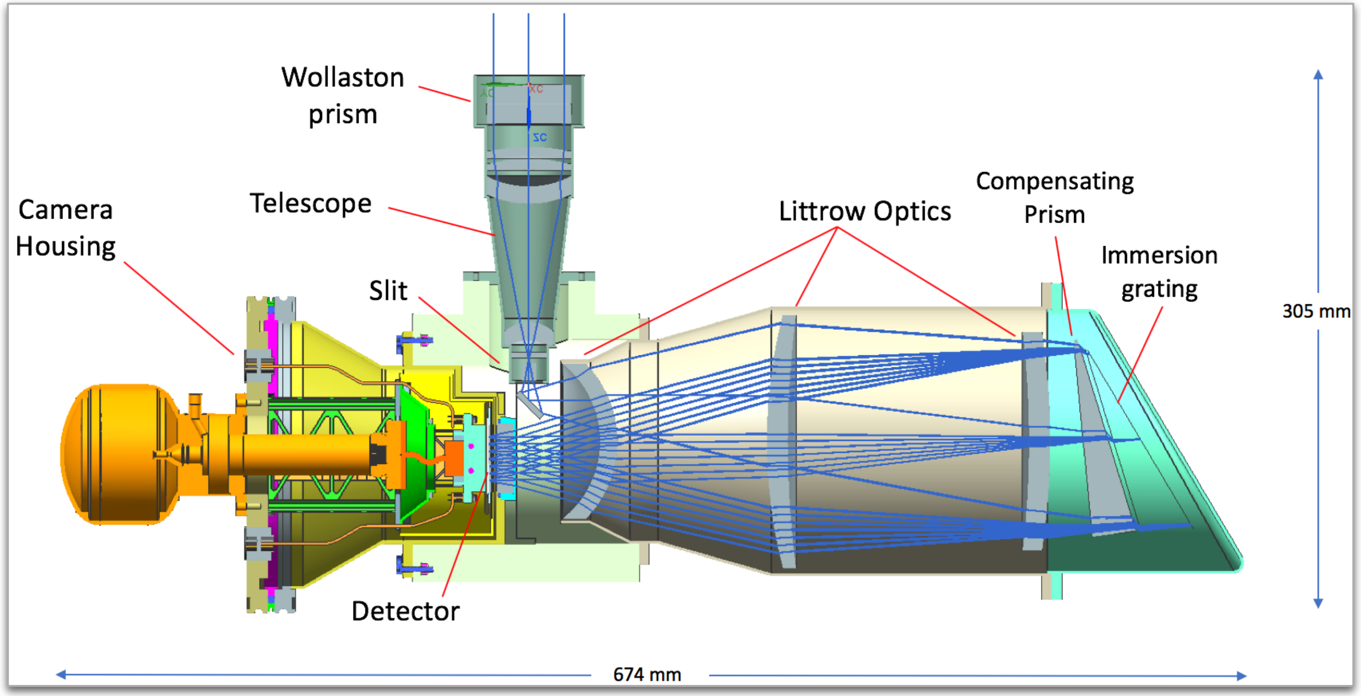


Conceptual **Opto-Mechanical** Layout

Instrument 2
(*1595 – 1659 nm, for CO2 and CH4 Remote Sensing*)

- Telescope aperture diameter: 35 mm
- Telescope focal length: 75.18 mm
- Telescope F/# : 2.11
- Ground Sample Distance: 168 m
- Slit width: 60 um
- Wavelength range: 61 nm
- Spectral Resolution: 0.15 nm
- R = 11,060
- Spectral dispersion: 814 pixels



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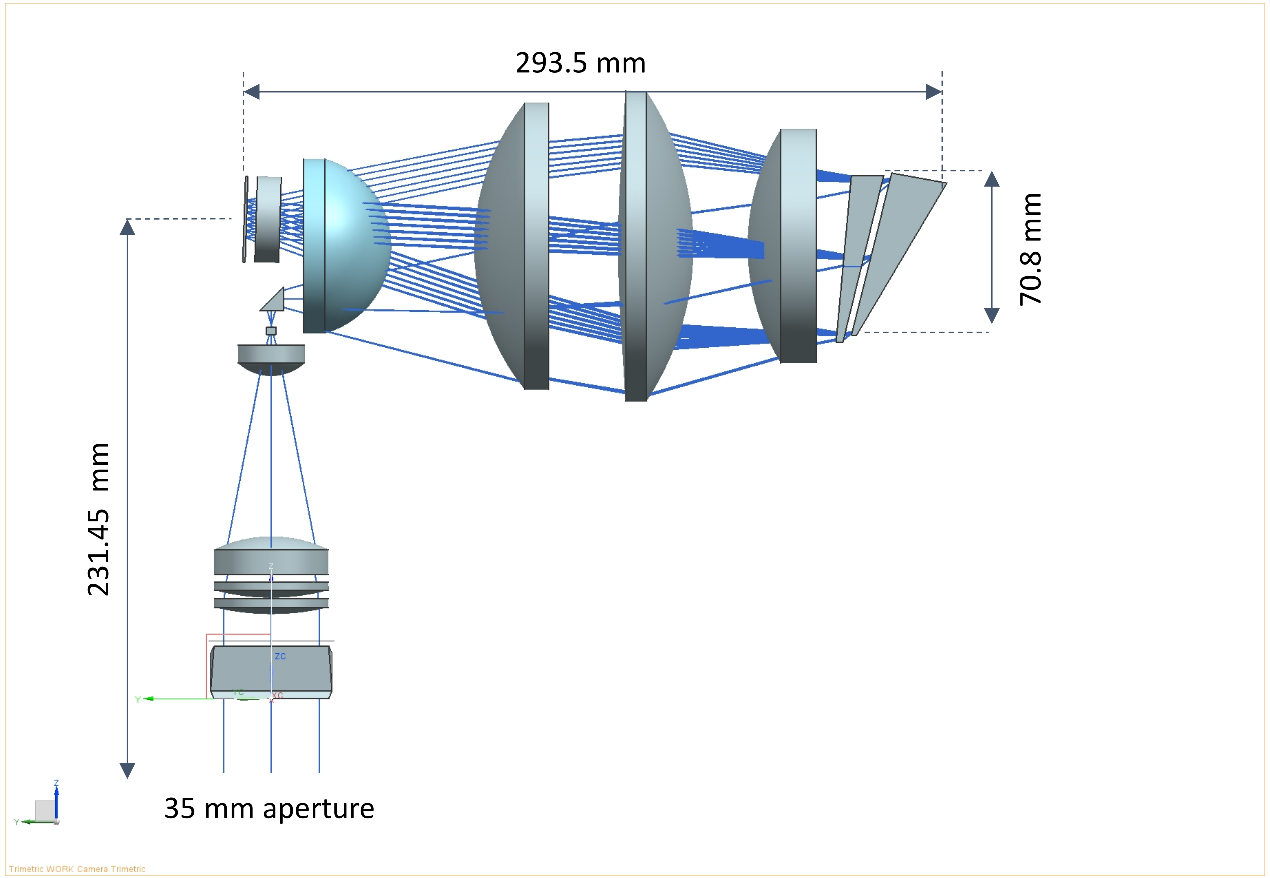
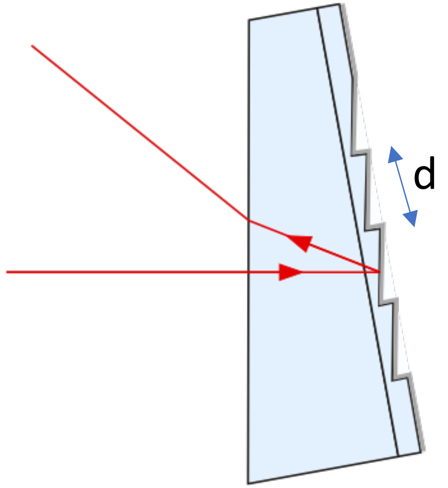
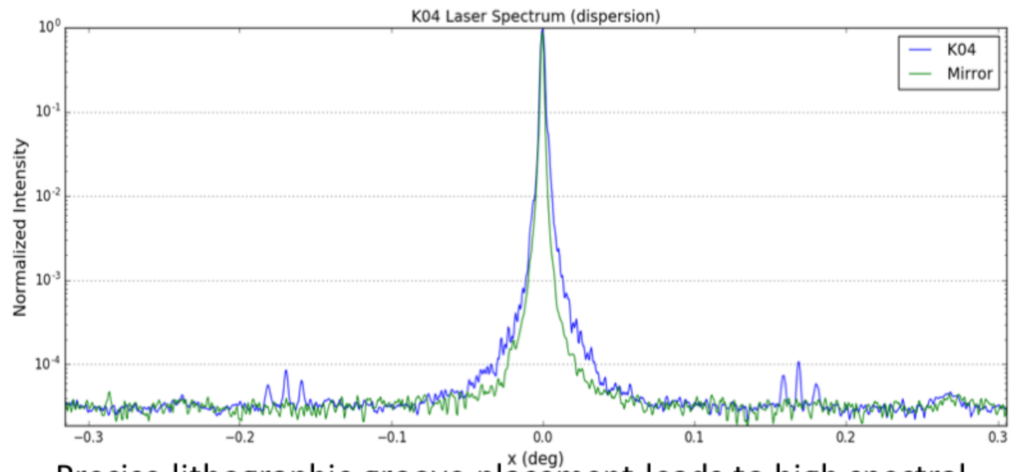


Key Technologies: Immersion Grating

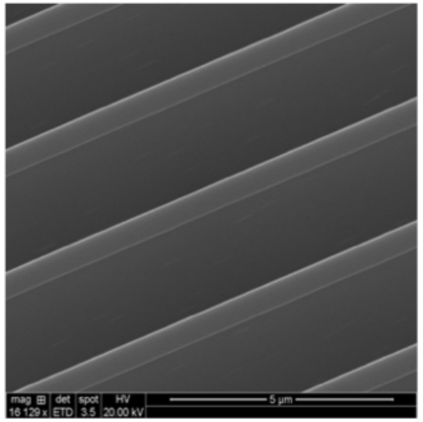
- Immersion grating reduces the size and mass of echelle gratings without sacrificing performance
  - Diffraction occurs internal to the material
  - Grating size scales as index of refraction, n
  - sin(a) + sin(b) = m $\frac{\lambda}{nd}$ where m is diffraction order, d is pitch, n is index of refraction and a and b are incident and diffracted angles
  - In silicon, grating facets are made via anisotropic etching resulting in atomic level features



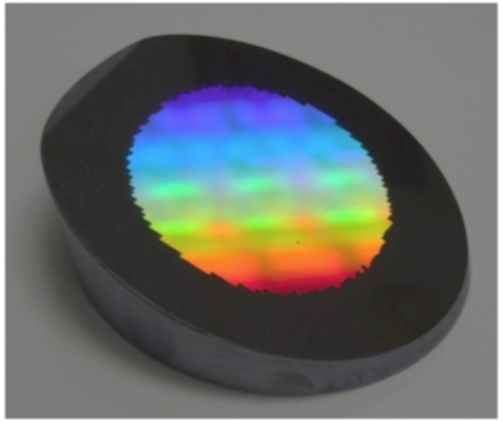
Glass prism with polymer grating



Precise lithographic groove placement leads to high spectral purity.



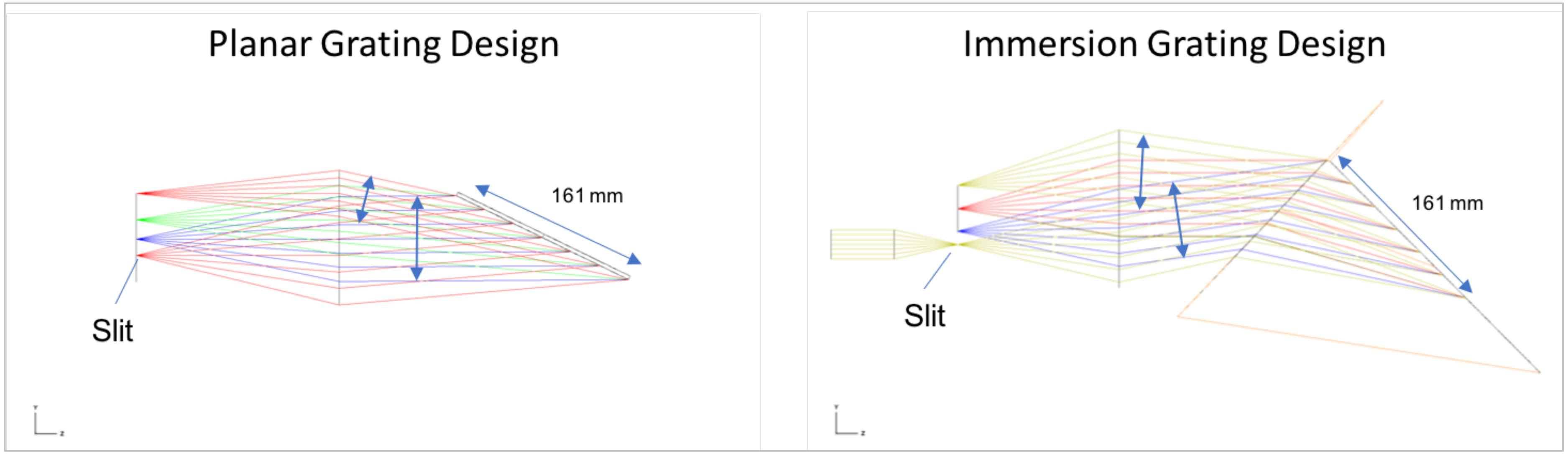
Groove structure



Grayscale E-beam Patterned Grating Etched into Silicon Prism
(Grating diameter 55 mm, Prism AR-coated on non-grating side)

Immersion Grating Correction of Anamorphic Compression

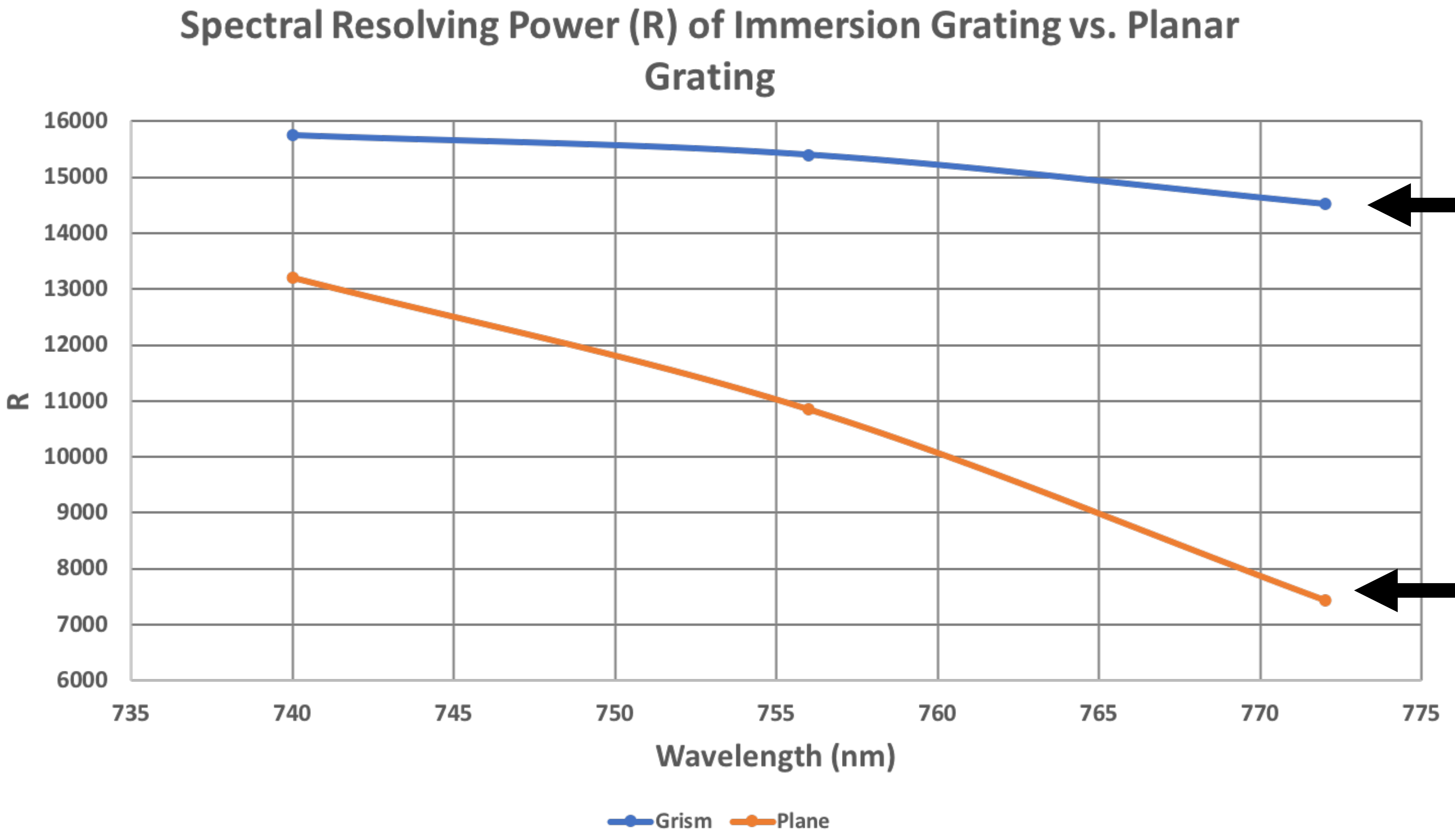
Immersion Grating Benefit: Reduction in Anamorphic Compression



- A planar grating causes anamorphic beam compression
- An immersed grating can be designed so that the anamorphism is largely compensated by the prism
- Anamorphic correction allows for more symmetric PSF over wavelength, which enables more uniform sampling over the detector

Immersion Grating and Spectral Resolving Power

Immersion Grating Benefit: Improvement in Resolving Power Uniformity Across Wavelength



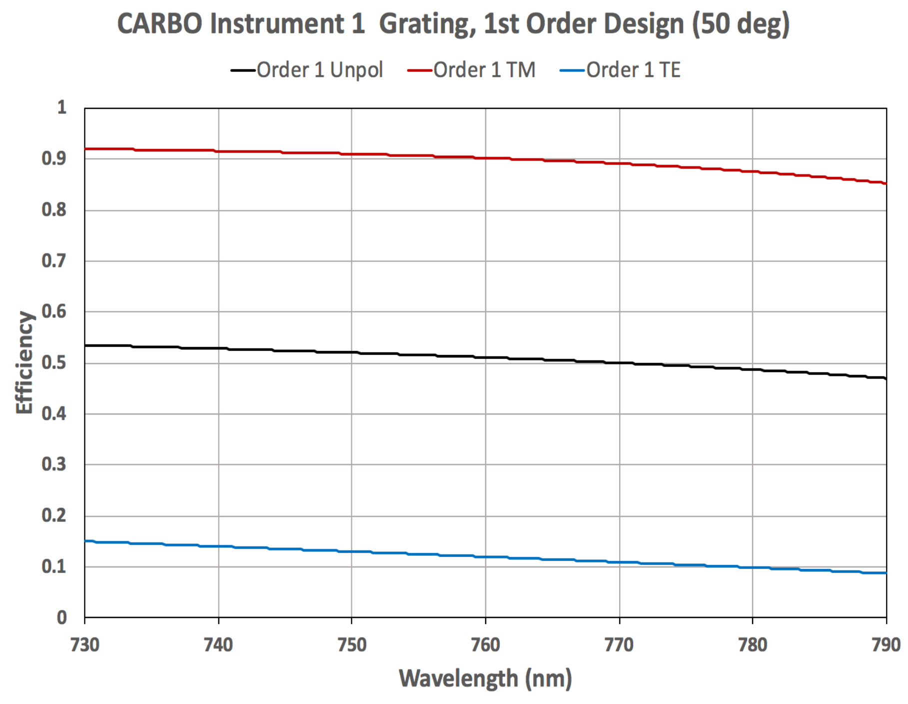
Grating length: 161 mm

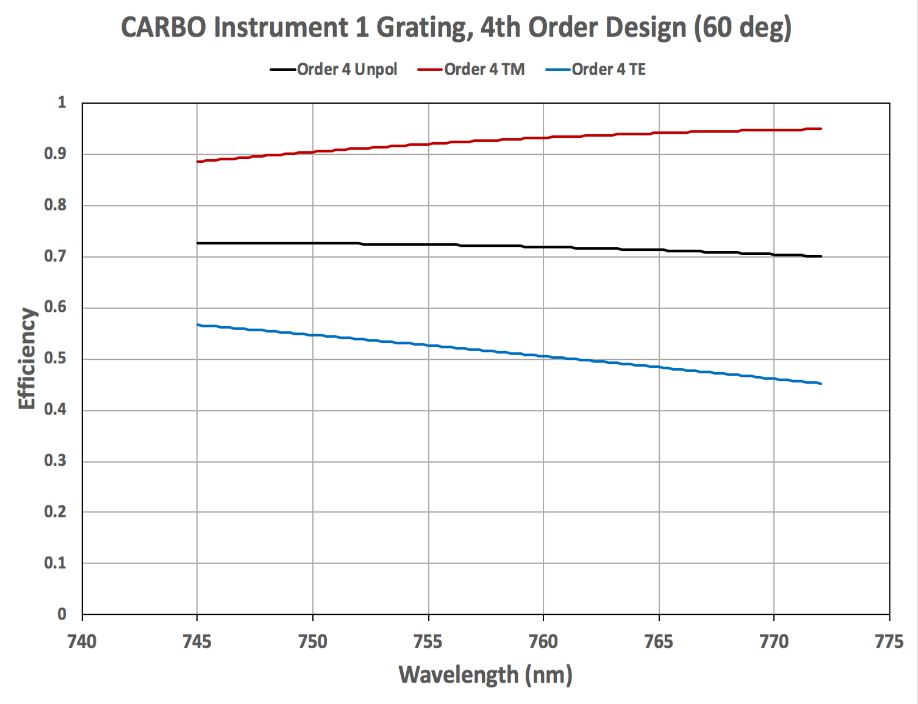
Immersion grating: Spectral resolving power varies by 1.08

Planar grating: Spectral resolving power varies by 1.8

Grating Efficiency Polarization Sensitivity

The two orthogonal polarization states have non-matching grating efficiencies

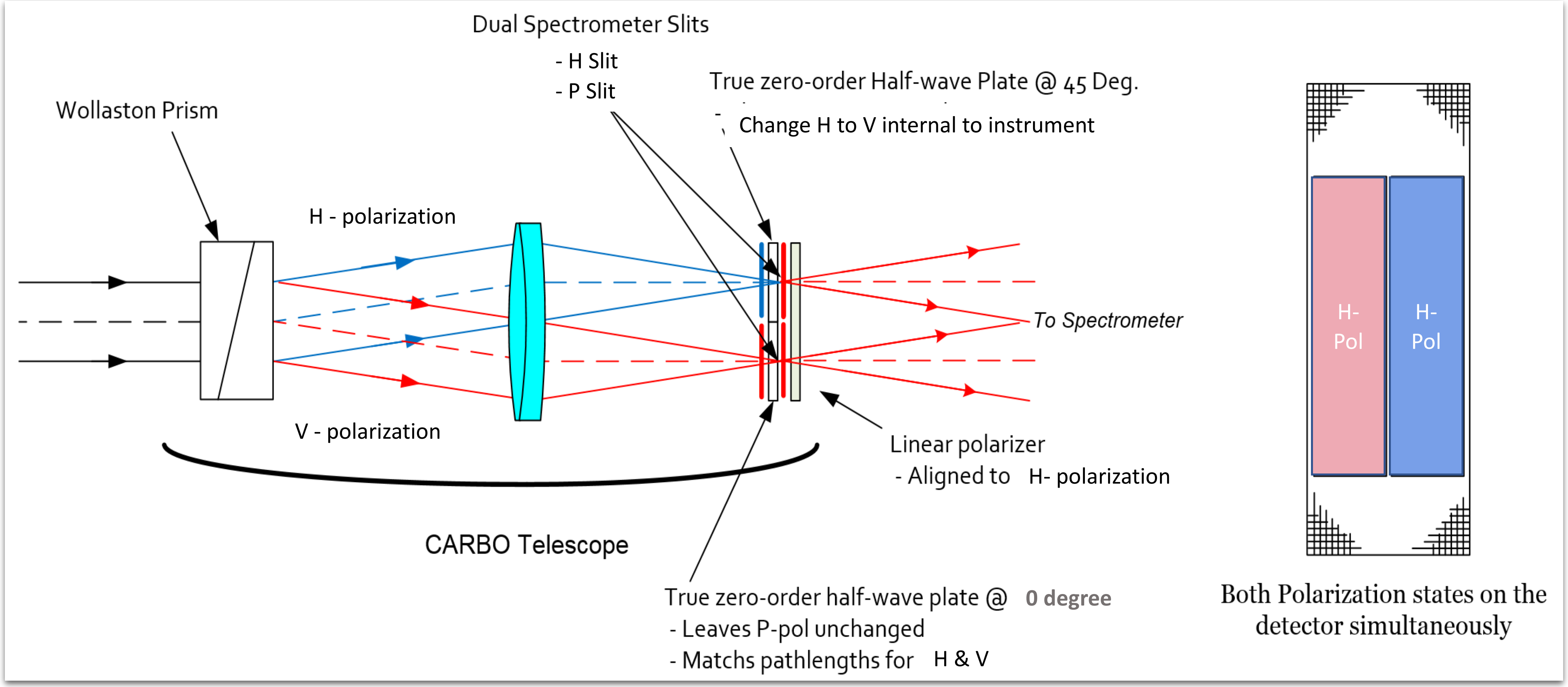




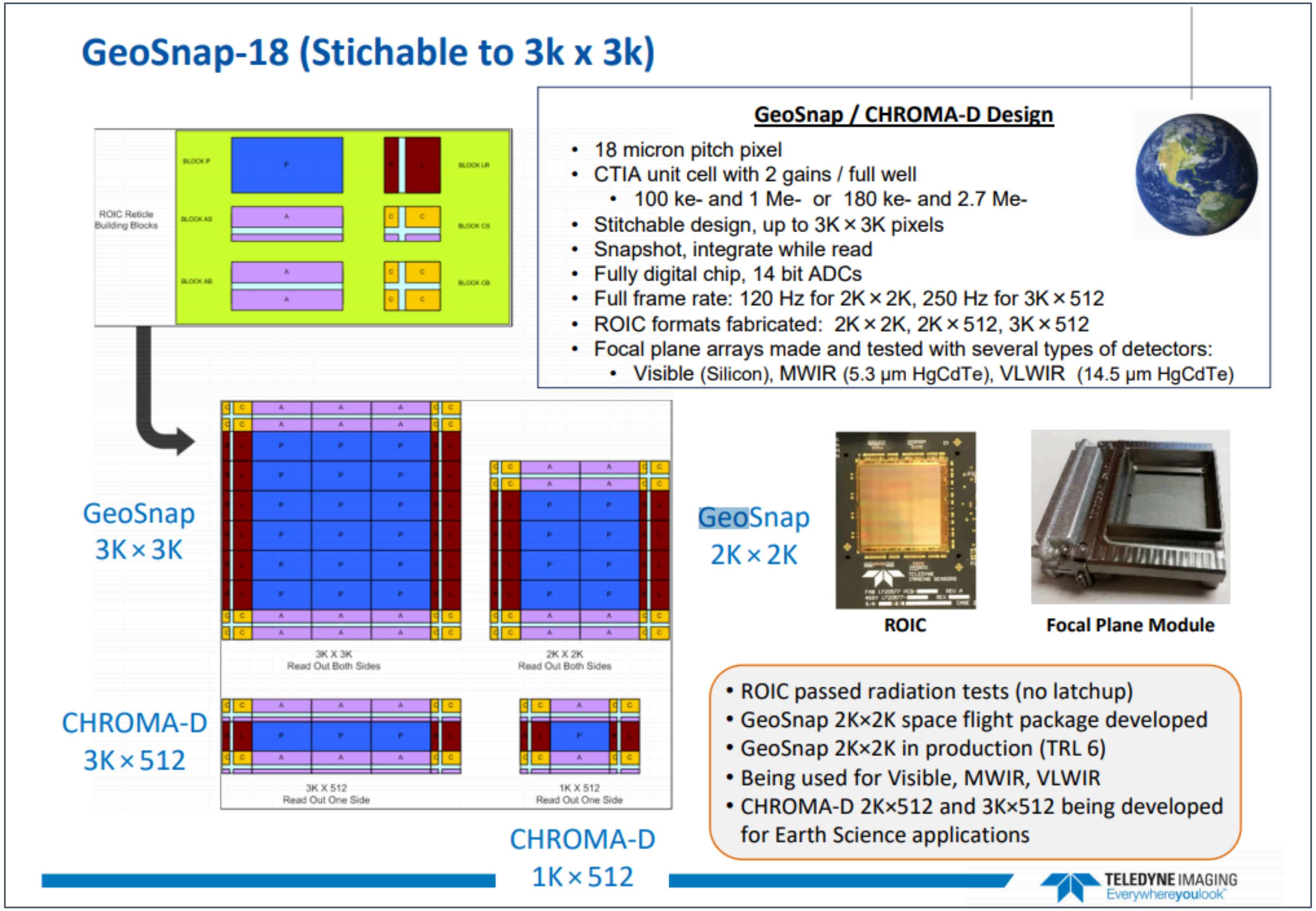
Highly polarization sensitive in 1st order

Polarization sensitive, even in 4th order

Key Technology: Polarization Sensing Optical Design



Large Format FPA, GeoSnap



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Key Technologies: Large Format FPA

- Latest infrared focal plane technologies from Teledyne Imaging Sensors (TIS)
- 18um pixel pitch HgCdTe detector hybridized to digital ROIC
- Variable array sizes of 2k x 500 (Chroma-D) and 2k x 2k (GeoSnap)
- On-chip digitization; without the need for complex analog-to-digital electronics supporting the FPA, the GeoSnap/CHROMA-D allows a simpler overall design for the CARBO instrument.

Detector Parameter	TIS 2.5um HgCdTe Performance
QE	
- 800nm	≥70% (≥80% goal)
- 1000nm	≥70% (≥80% goal)
- 1230nm	≥70% (≥80% goal)
- 2000nm	≥70% (≥80% goal)
Median Dark Current (140K)	100 e-/s/pix
Operability	≥95% (≥99% goal)

Typical Performance for TIS 2.5um-cutoff HgCdTe detectors

ROIC Version		High Gain	Low Gain
A0	Full Well (e-)	100,000	1,000,000
	Readout Noise (e- RMS)	25	150
A1	Full Well (e-)	180,000	2,700,000
	Readout Noise (e- RMS)	35	300

Predicted full well and readout noise performance for the 2 different version of the CHROMA-D ROIC

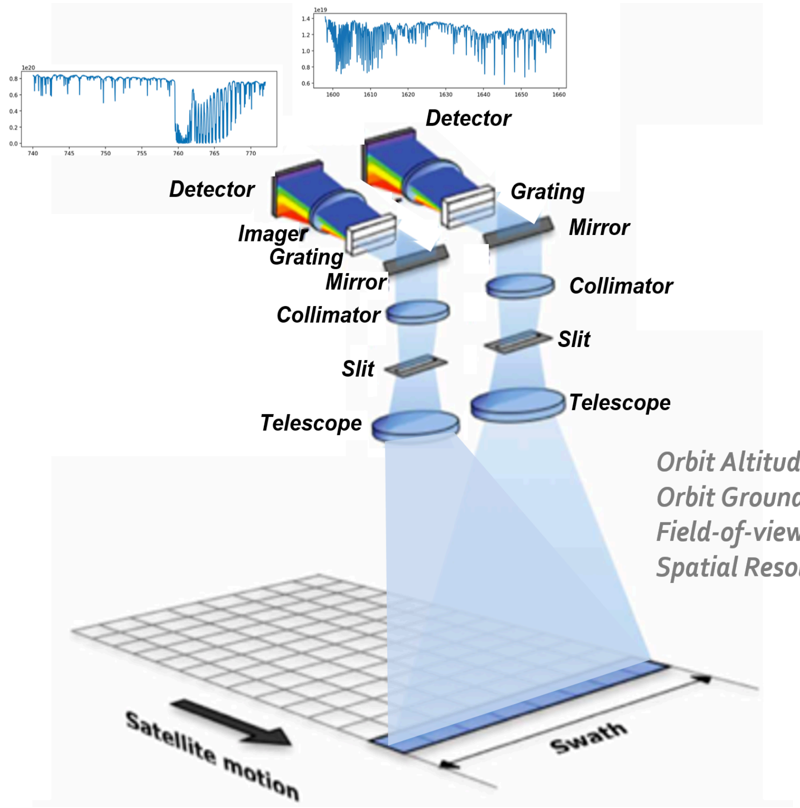
FPA Noise Assumptions for Performance Estimate

	CHROMA-A	CHROMA-D / GeoSnap
Charge Capacity (k e-)	1000	180
Pixel pitch (μ)	30	18
Dark Current (e-/pix/s) @ 140 K	279	100
Dark Noise (e-/pix)	6.4	3.8
Read Noise (e- rms)	129	35
Electronics Noise (e- rms)	70	N/A
Quantization Noise (e- rms)	15.3	11

The noise values used for CHROMA-A are for an engineering-grade FPA, and the noise values for CHROMA-D are based on theoretical projected values. Additionally, the electronics noise for the CHROMA-A FPAs is based on the JPL-designed CHROMA-A electronics. *Dark Current values estimated at the CARBO operating temperature using “Rule07” with a 100x derating factor

Radiometric Performance Estimate

- The engineering design work is guided by Radiometric performance estimate (analysis of SNR), which is a function of:
  - Radiometry over the band
  - Observational Scenarios (albedo and SZA)
  - Instrument parameters
  - Throughput of the system
  - FPA noise performance
  - Integration time
  - Fabrication constraints



Orbit Altitude: 705 km
Orbit Ground Velocity: 6.767 km/sec
Field-of-view: 12 deg.
Spatial Resolution: 2 km x 2 km

Radiometric Performance Estimate

	Instrument 1	Instrument 2
Wavelength (nm)	745 - 772	1598 - 1659
Spectral Resolution (nm)	0.05	0.15
FPA	GeoSnap-18 (2k x 2k)	
Charge Capacity (k e-)	180	
Pixel pitch (μ)	18	
GSD (km)	0.240	0.169
Image footprint on FPA (pixels)	1080 x 1286	813 x 1746
Signal Per Pixel (e-)	3527	3228
Noise Per Pixel (e-)	70	68
SNR per Pixel	50	48
Spatial Pixels	8.3	11.9
Spectral Pixels	2	
Frames	2	
Total SNR (per 2km x 2km spatial resolution element @ 5% albedo and 50 degree SZA)	412	464
SNR Threshold	300	350

Instrument 1 SNR estimates are based on: spectral radiance at top of the atmosphere 402 W/m^2/sr/um, albedo 5%, solar zenith angle 50^o, FOV 12^o per S and P polarization, ground swath 148 km, F/2.11, aperture 25 mm, slit width 60 um, total optical transmission 0.71, integration time 0.148 s.

Instrument 2 SNR estimates are based on: spectral radiance at top of the atmosphere 60.2 W/m^2/sr/um, albedo 5%, solar zenith angle 50^o, FOV 12^o per S and P polarization, ground swath 148 km, F/2.11, aperture 35 mm, slit width 60 um, total optical transmission 0.71, integration time 0.148 s.

Summary and Conclusion

- CARBO is a tech demo instrument, funded by NASA's Instrument Incubator Program
- CARBO consists of a wide-FOV suite of instruments to measure CO2, CH4, CO and enhanced SIF within a 2x2 km^2 area at a high spectral resolution (0.5 – 0.15 nm) with a weekly revisit rate
- CARBO suite of instruments advance the following key technologies:
    - Immersion gratings
    - Large format GeoSnap FPAs
    - Simultaneous polarization sensing
    - Modular architecture, same form factor, on a common platform
- JPL designs, builds and tests instruments 1 and 2 with GeoSnap, and designs instruments 3 and 4